LCA Case Studies

End-of-Life of a Polypropylene Bumper Skin

Some Key Elements for a Pragmatic Environmental Management

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Abstract. The aim of this article is to show how, at PSA peugeot-citroën, Life Cycle Assessment (LCA) is used as a tool to evaluate the environmental burdens associated with a product, a process or an activity by identifying and quantifying energy, material used and wastes released to the environment.
In this paper, the LCA methodology is applied to a practical case study: the comparison of various end-of-life scenarios (recycling versus incineration with or without energy recovery with landfill as a reference) for a polypropylene (PP) bumper skin. All the LCA steps (goal, inventory, impacts assessment, interpretation) are developed in this study. It is shown that in the particular case of PP, incineration with energy recovery is on an environmental point of view between 30 and 60% recycling. However, due to some uncertainties on data quality, the absolute values of the inputs/outputs for the inventory step may not be sufficient to allow strong decision making and the use of the factorial experiments (Taguchi) is then proposed to select the dominant parameters of the study. Strong environmental conclusions can then be drawn from the study.

Keywords: Bumper skin; case studies; LCA methodology; Life Cycle Assessment; peugeot-citroën; polypropylene bumper skin

Introduction

As the environment has become a strategic issue of increasing competitiveness, industrial companies like PSA Peugeot-Citroën are becoming more interested in being able to study the environmental consequences of their products and processes.

It is now recognised that there is a need for a global environmental approach comprising the whole life cycle of a product (raw material, manufacturing, use and end-of-life) preventing the neglect or the shift of potential environmental effects. Life Cycle Assessments (LCA) have undergone a significant development. It has been defined as a tool that evaluates the environmental burdens associated with a product, a process, or a human activity by identifying and quantifying energy, material used, air and water emissions, and waste released to the environment. LCA also identifies and assesses impacts. The rise of oil prices in the seventies induced a well known fall of the car consumption and the increasing use of polymeric materials. Concomitantly, major concerns arose within the European nations regarding the management of the end-of-life vehicles and a European Directive is under discussion for imposing recycling rates on consumer goods in general and especially the automobile. It is therefore important to assess the real environmental potential of recycling compared to incineration with energy recovery and the present reality, landfill.

The LCA methodology is applied in this paper throughout a practical case study, a polypropylene bumper skin and six main alternatives of end-of-life scenarios, landfill, 30, 60 and 90% recycling, as well as incineration with and without energy recovery. All the LCA steps (goal, inventory, impact assessment and interpretation) are developed in this study. Three different impact assessment methodologies are compared and ranked. Finally, the Taguchi plans have been applied to evaluate the sensitivity of the results to the hypotheses.

1 Goal Definition and Scope of the Study

The aim of the study is then to examine the environmental merits of various end-of-life scenarios of a polypropylene (PP) bumper skin compared to the actual option, i.e. landfill taken as the reference. The following end-of-life scenarios have been studied: recycling (with different rates 30, 60 and 90%), incineration with or without energy recovery.

1.1 Functional unit

The functional unit describing the studied system is crucial as it defines a product's performance and is essential for comparisons [1]. This study deals with a particular component: a bumper. Identical activities in compared alternatives are usually omitted [2] and consequently the use phase, which is rigorously equivalent whatever the scenario, is not taken into account. Moreover its importance would have hidden the differences between the various scenarios since it represents 60 to 80% of the total [3,4]. In the present case, the functional unit is a 4 kg unpainted polypropylene bumper skin and all the steps, from raw material extraction up to end-of-life, except the use phase.

1.2 Phases of life cycle

The following steps of the life cycle have been taken into account:

- Raw material production: production of PP granulate
- Transport of PP granulate to the injection plant
- Injection moulding of PP bumper skin

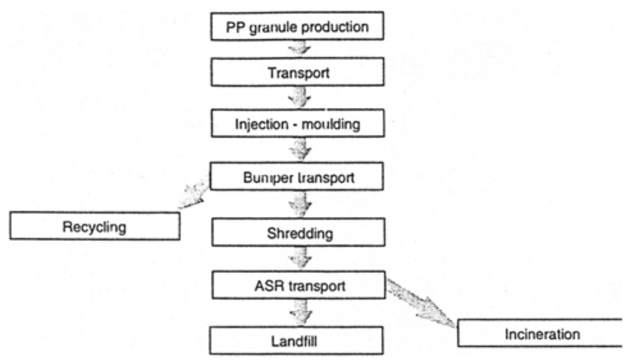

Fig. 1: Process tree for PP bumper skin

- Transport of PP bumper skin for assembling at the automotive plant
- End-of-life of PP bumper skin with three possible routes:
- Recycling including shredding, washing and reprocessing
- Shredding and transportation of the ASR (Automotive Shredder Residue) to the landfill
- Incineration with or without energy recovery.

The process tree for the PP bumper skin is summarised Fig. 1.

1.3 System boundaries

The main difficulty of the study is to place the system boundaries. In theory, four fields have to be taken into account in an LCA [5]: industrial processes, energy and its production, substructures, and human activities. However, Boustead and Hancock [6] have demonstrated that the first two points on their own represent 95% of the whole cycle energy. Consequently, the two latter fields are usually ignored [5]. Moreover, it should be noted that the influence of factory building would have been very small compared to the number of bumper skins produced.

Concerning the transportation phases, the fabrication of the trucks is neglected as well as the construction and the maintenance of the roads. Only the energy consumption and the air emissions of the trucks are considered.

Regarding incineration and recycling, the boundaries have to be defined in accordance with the definition of the functional unit. After recycling (resp. incineration), recycled material (resp. some energy) is available. Fig. 2 presents the theoretical life cycle of system 1. If the x quantity of recycled material (resp. energy) is used in the same application, the 1-x (resp. energy) goes into another system (2). The difficulty is to put the boundaries between the two systems and to isolate the system under study (i.e. system 1). In general, allocations between systems should be avoided by expanding the boundaries (ISO 14041). Several authors [2,7,8] have introduced this concept of several functional units fulfilled by a system to take into account the production of 1-x recycled material (resp. energy) going into another system. Then the system is enlarged by adding subsystems that provide missing functions to relative alternative and the functional unit is modified consequently. This solution is the most transparent and scientific.

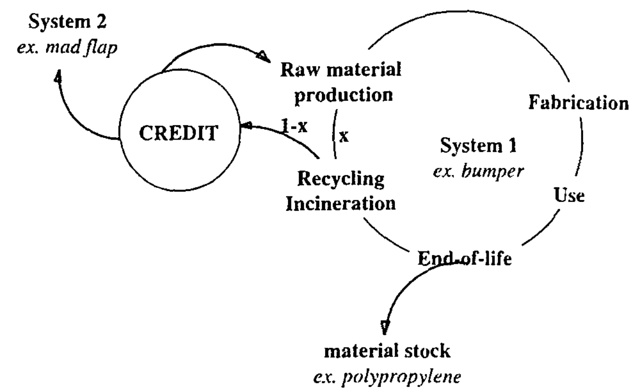

Fig. 2: Theoretical life cycle

However the expansion of the system boundaries is practically unmanageable, especially when system 2 is unknown. The added system increases the size of the original system and does not facilitate the inventory calculation; in addition, it complicates the interpretation of the results.

Finnveden [9] has also proposed the use of allocation rules based on arbitrary numbers: between 0 and 100% of recycling is allocated to the studied system. This splits the environmental inputs and outputs associated with recycling or incineration and is very subjective.

However, it can be noted that the 1-x quantity of recycled material (resp. energy) represents a material (resp. energy) credit and avoids somewhere in another system the consumption of virgin material (resp. energy). Consequently, it does not matter on an environmental point of view within which system the recycled material (resp. energy) will be used. Therefore, a 100% allocation rules of the recycling or incinerating to the system 1 has been postulated, creating a closed loop. It should be noted that recycled material is reused in the same application in this calculation and it does not take into account the quality loss of material due to recycling.

1.4 Hypotheses

For the study, the following assumptions have been made: Concerning all the transportation phases, 20-ton trucks have been chosen, empty returns are assumed and the Boustead software transport model has been used. For electricity consumption, the French electricity model from the Boustead software has been chosen. In the following paragraph, for transportation (resp. electricity) only the distance (resp. energy consumption) is specified.

- PP granulate production: APME (Association of Plastic Manufacturers in Europe) data for PP granulate production, 4 kg of PP granule for each bumper skin.
- Granulate transport to plant: a 200 km-long drive.
- Bumper skin moulding: a 4 kg bumper skin for the moulding step, no losses during processing, 18 MJ electricity per injected bumper.
- Bumper transport to manufacturing plant: 250 bumpers transported in each truck, a 200 km-long drive.
- Assembling: negligible.
- Shredding: a 0.3 MJ electric consumption per bumper, bumper and car simultaneously shredded.

- Transport of ASR (Automotive Shredder Residue): fully loaded trucks, a 50 km-long drive.
- Landfill: the whole bumper skin is put in a landfill which is considered as outside of the system boundaries. So, no emission at this step. This assumption seems to be acceptable as the polypropylene is stable and does not induces specific emissions of pollutants.
- Incineration: No public data is available concerning the incineration of PP. Consequently, burning experiments have been performed at L.N.E. (Laboratoire National d'Essais at Trappes, France) on PP and on a reference fuel. During those experiments, only air emissions (CO, CO_2, and SO_x), and energetic content of the two materials have been measured.
- Recycling: a 850 km transportation, a 1.7 MJ of electric consumption per kg recycled.

2 Inventory

All the calculations have been performed with 'The Boustead Model'. The comparison focused first on Life Cycle Inventory, in particular on energy consumption and on CO_2 emissions. For these two parameters, landfill is taken as a reference and scaled to a value of 100, and the other scenarios are shown in comparison to this reference. The results for energy consumption are presented in **Fig. 3**. For each scenario, the total energy consumption from raw material extraction up to end-of-life is presented.

As it can be seen, energy consumption for landfill and incineration without energy recovery are equal. Therefore, there is no advantage for incineration without energy recovery compared to landfill. For incineration with energy recovery, energy consumption is 44. For 30% and 90% recycling, energy consumption is respectively 85 and 50. Compared to landfill, recycling and incineration with energy recovery seem to be interesting in terms of energy consumption. Moreover, the higher the recycling rate, the lower the energy consumption.

Although the 90% recycling scenario has the smallest energy consumption, and because of a small gap (Δ = 6) with energy recovery, these two scenarios have to be considered equivalent.

For each scenario the total CO_2 emissions for the complete life cycle of the PP bumper are also presented in **Fig. 4**. For

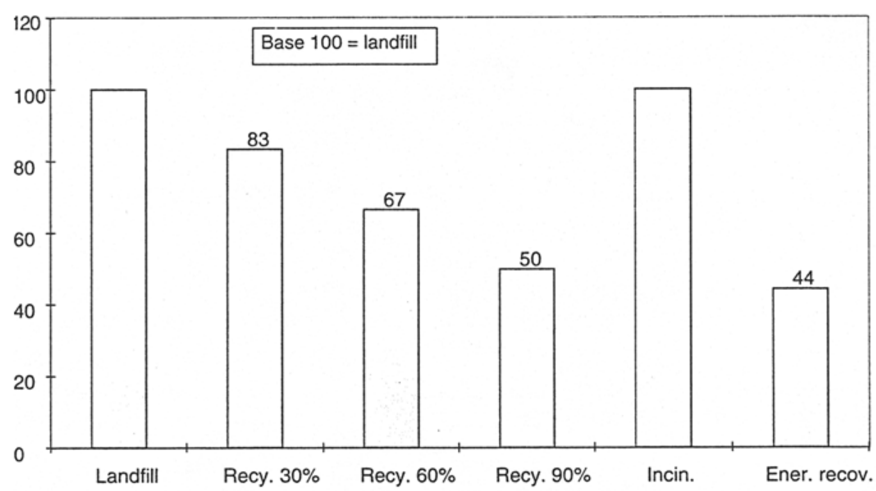

Fig. 3: Energy consumption of various scenarios compared to landfill (basis 100 = 409 MJ)

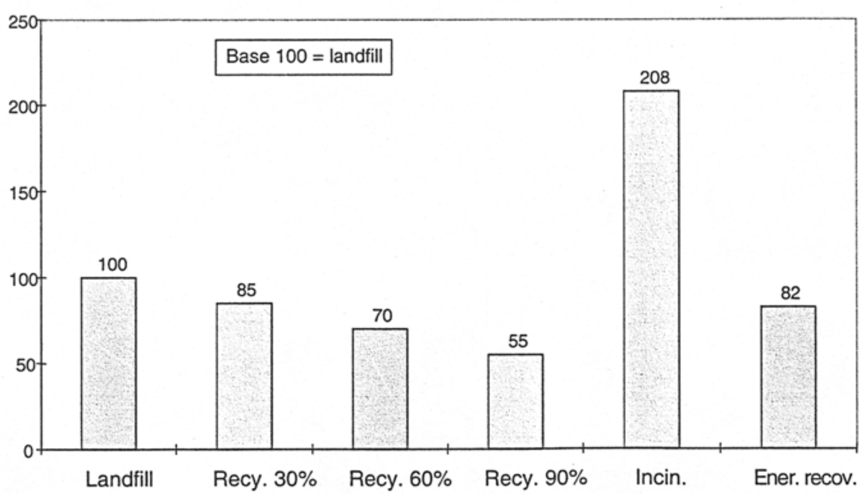

Fig. 4: CO_2 emissions of various scenarios compared to landfill (basis 100 = 10 Kg)

30% and 90% recycling, CO_2 emissions are respectively 85 and 55. Recycling is therefore more interesting in terms of CO_2 emissions than landfill. As for energy, the higher the recycling rate, the lower the CO_2. In the case of incineration with (resp. without) energy recovery, CO_2 emissions are 82 (resp. 208). Indeed, due to this essential hypothesis for the comparison of end-of-life scenarios, the CO_2 emissions induced by the PP incineration are compared to those of a reference fuel which is usually used in thermal power stations. The chemical nature of PP (saturated hydrocarbon chains) compared to that of the fuel induces a higher calorific power for PP and limits the CO_2 emissions. Then the CO_2 emissions with energy recovery are between the emissions of 30% and 60% recycling.

The results of this inventory focused on energy consumption and CO_2 emissions are not sufficient to appreciate the whole environmental merits of the various end-of-life scenarios. A more comprehensive picture is then needed which cannot be done with the full results of the inventory, but only through the impact assessment.

3 Impact Assessment

The impact assessment step is still under development. Due to a lack of consensus, the general approach recommended by ISO 14040-14043 is to calculate for relevant categories, category indicators. The aggregation of the indicators is an optional element of the ISO 14042. Then, various methodologies have been used in order to compare the results of the scenarios: The CML (Center Milieukunde Leiden) method, which follows the line of ISO, the EPS (Environmental Priority Strategy) [10,11] method, which integrates a weighting of the impacts, and the Critical volumes approach (Buwal), are used.

The use of several methods will allow the comparison of the results and show if they are method dependant. Whatever the method and the criteria, landfill has been taken as a reference and scaled to a value of 100.

3.1 EPS (Environmental Priority Strategy) method

The results with the EPS method are shown in Fig. 5. For each scenario, the environmental impact is calculated in terms of ELU and scaled in comparison to the reference. The value of 100 is assigned to the reference.

As it can be seen, 30% (resp. 90%) recycling gives a value of 80 (resp. 41). Compared to the landfill scenario, the recycling appears to be interesting. The higher the recycling rates, the lower the ELU quantity. Incineration without energy recovery shows a very high impact compared to the other scenarios (value of 124). This option causes air emissions and does not provide any environmental credit, except for the reduction of solid wastes (see, Fig. 5). Incineration with energy recovery, with a value of 43, and 90% recycling, with a value of 41, are equivalent and, undoubtedly, are the most favourable scenarios.

3.2 Critical volumes approach

In this method, the environmental impact is assessed by four criteria: energy consumption, critical air volume, critical water volume and amounts of solid wastes[12,5].

Fig. 6 presents the results of the critical volume approach with the study. All the parameters are represented on the same graph.

In terms of energy consumption, the results are rigorously the same as those obtained from the inventory (see, Fig. 3).

Owing to a lack of data, incineration does not take into account water emission. So this critical water volume criterion is equal to landfill and therefore is absolutely irrelevant

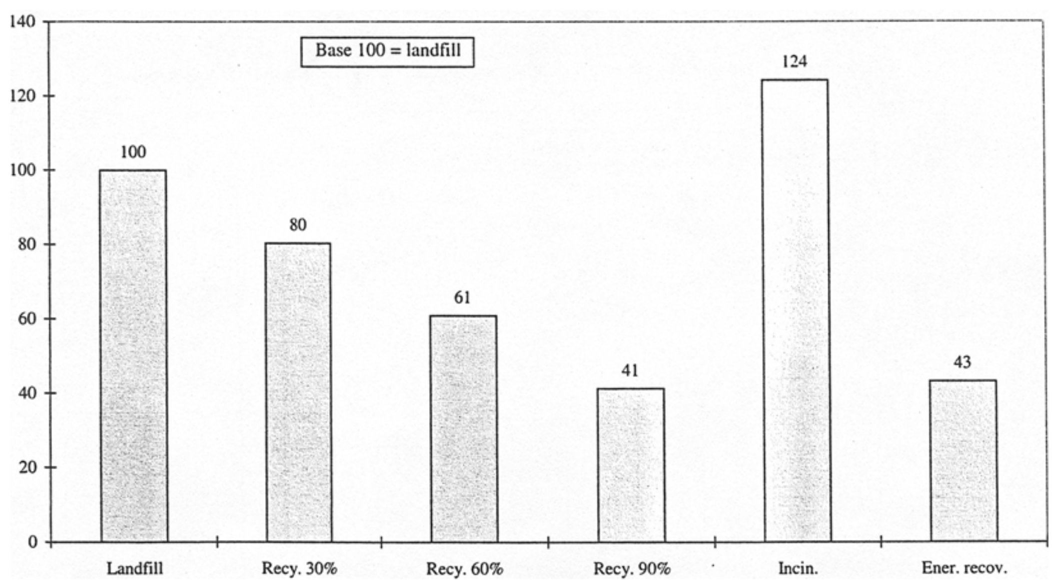

Fig. 5: Results of various scenarios compared to landfill with the EPS method (basis 100 = 4.1 ELU)

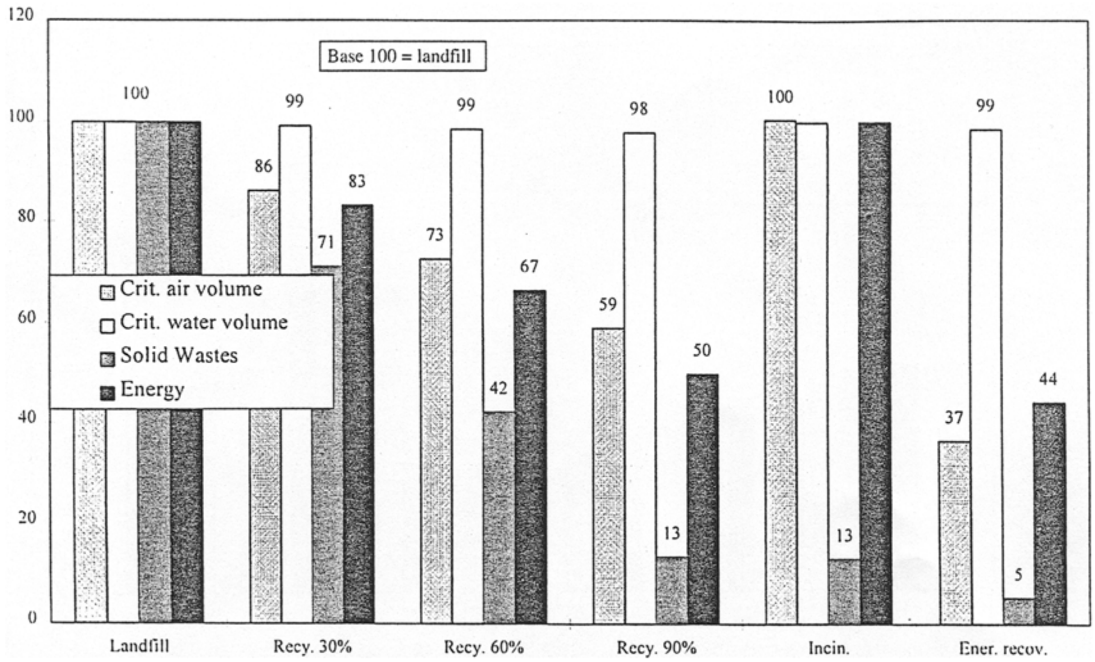

Fig. 6: Results with the Critical Volume approach (Critical air volume basis 100 = 4.3 10^6 m^3, critical water volume basis 100 = 903 m^3, solid wastes basis 100 = 4.2 kg, energy basis 100 = 409 MJ)

for comparison purposes. In the case of 30% (resp. 90%) recycling, the critical water volume criterion has a value of 99 (resp. 98). This is explained by the relationship between critical water volume and recycling rate. Recycling appears to be interesting compared to landfill, despite a small difference ($\Delta < 10$) and no strong conclusion can be drawn from that parameter consequently. In terms of critical air volume, 30% (resp. 90%) recycling has the value of 86 (resp. 59), thus confirming the previous trend. There is no advantage in incinerating without energy recovery that shows a value of 100. However, incineration with energy recovery with a value of 37, is undoubtedly the most favourable scenario.

Considering the solid wastes, the quantity of solid wastes for 30 and 90 % recycling is 71 and 13, resp. The incineration without energy recovery and 90% recycling have the same value of 13. The incineration with energy recovery decreases the waste quantity to values below 10 and is then the most favourable scenario.

From results with the critical volume approach, it can be concluded that energy recovery is the best scenario in terms of critical air volume, solid wastes and energy. However, it is not possible to clearly distinguish the scenarios with the critical water parameter.

3.3 CML method

In the CML method, the loadings are summed up according to their contribution to environmental effects. For each environmental theme, a potential impact is calculated according to the equivalency factors proposed by the method. The impact categories may have different scaling: global, continental, regional and local. In practical LCA studies, major impact categories or subcategories may be excluded by concentrating on some global and regional impacts. Human health and welfare (including occupational health and noise), or non-chemical, ecological impacts such as landscape demolition, habitat destruction and other local type impacts are often excluded [13]. However, each practitioner has to select the criteria he wants to evaluate among the criteria proposed by the method. This must be done in relation with the goal and scope of the study. Therefore, this practical study concentrates on global impact categories (global warming, eutrophication, energy, resources and acidification) and excludes regional and local type impacts. Human health and welfare impacts are also excluded.

Concerning ozone depletion, the participating flux (CFC, HCFC, brominated compounds) are very low and equivalent, whatever the scenarios. Therefore, no attention has been paid to this parameter.

The following environmental themes are considered [14-16]:

- Resources depletion (relative to the world-wide stores)
- Global warming potential (relative to 1 kg CO_2)
- Acidification (relative to 1 kg SO_2)
- Nutrification (relative to 1 kg PO_4^{3-})
- Ozone depletion (relative to 1 kg CFC-11)

The results are shown in **Fig. 7** and, as it can be seen, incineration without energy recovery does not allow any economy on natural resources, whereas incineration with energy recovery allows an economy of more than half of the total natural resource consumption. Recycling causes a reduction of consumption of natural resources and the economy is directly related to the recycling rate. Consequently, incineration with energy recovery with the value of 25 is the most favourable scenario followed by recycling 90% with the value of 38.

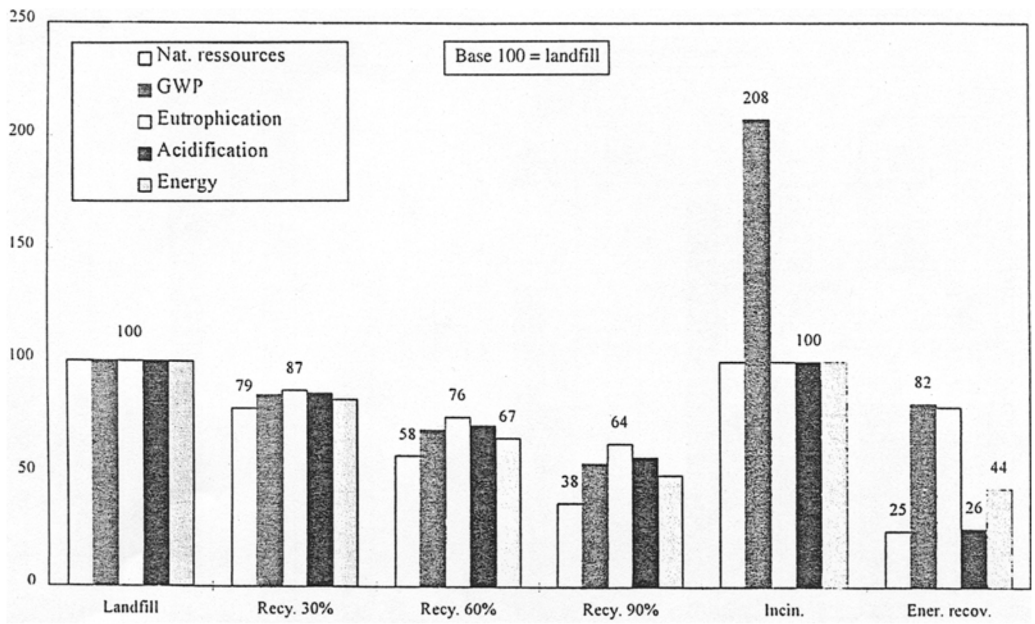

Fig. 7: Results with the CML method (natural resources basis 100 = 0.2, GWP basis 100 = 10 kg eq. CO_2, eutrophication basis 100 = 8.6 10^{-3} kg eq. PO_4^{3-}, acidification basis 100 = 0.1 kg eq. SO_2, energy basis 100 = 409 MJ)

Concerning energy consumption, conclusions have already been drawn (Fig. 3). For 30% (resp. 90%) recycling, the global warming potential (GWP) is 85 (resp. 55). Recycling is more interesting than landfill in terms of GWP, and the more the recycling rate increases, the more GWP decreases.

Incineration without energy recovery shows a value of 208, whereas incineration with energy recovery shows a value of 82. So, incineration has a very high impact and can be very prejudicial on GWP. Anyway, incineration with energy recovery is in terms of GWP between recycling 30% and recycling 60%, thus confirming the previous results on CO_2 emissions (see, Fig. 4).

Regarding eutrophication, 30 and 90% recycling have a value of 87 and 64, resp. This decrease is closely related to the increasing recycling rate. As in the case of critical water volume, eutrophication criterion does not make any sense for incineration. Therefore, landfill and incineration (with and without energy recovery) together have a value of 100. Although recycling is interesting in terms of eutrophication, no overall conclusion can be drawn.

Concerning acidification, incineration without energy recovery is equivalent to the landfill scenario. Incineration with energy recovery decreases the acidification potential (value of 26) due to the absence of SO_x during PP burning. Recycling decreases acidification to a value of 86 for 30% recycling and to 58 for 90% recycling. Incineration with energy recovery is the most favourable scenario in terms of acidification potential.

From those results with the CML method, it can be concluded that incineration with energy recovery is the most favourable scenario for energy, natural resources and acidification. For the GWP and eutrophication, incineration with energy recovery is located between recycling 30% and recycling 60%. For eutrophication, no conclusion can be drawn.

3.4 Conclusion of the impact assessment

The Critical Volume method and results obtained on energy, natural resources, acidification criteria have shown that incineration with energy recovery is the most favourable option for the environment. For critical water volume and eutrophication, no conclusion can be drawn since no data about water in the case of incineration is available. Only air emissions have been taken into account for incineration. The results obtained with the EPS method showed that incineration with energy recovery and 90% recycling are equivalent. For the impact GWP and eutrophication, incineration with energy recovery is between recycling 30 and 90%. Incineration with energy recovery cannot be neglected and is as environmental friendly between 30 and 90% recycling. Although all the impact assessment do not follow the line of ISO, they give the same trends.

4 Sensitivity Analysis by Means of Taguchi Plan

The quality of the data and the confidence in the robustness of the results is a crucial point for the LCA applications. Various methods exist to estimate the effects of the chosen assumptions and data on the results of a study (ISO 14041).

Two alternatives can be evaluated first. Either a parameter range is determined by measuring or by estimating each parameter of the study. Then a calculation of the inventory with the minimum and maximum of each parameter is performed. The influence of the parameter is approached by comparing the results obtained with the various values taken by each parameter (minimum value, value taken in the study, maximum value). Or the value of the parameter for which the conclusions of a comparison are changed is sought and the probability of encountering this particular parameter value is estimated.

These two approaches are quite cumbersome because it is necessary to assess each of them separately and to make new calculations for each parameter in order to qualify its influence independently of the others parameters. This involves a great number of operations as two calculations have to be done for each parameter in the case of the first method, the second one involving either the development of a special function to determine the value which changes the comparison between A and B for a particular parameter or a step-by-step approach to find the value. Henceforth, an application of such methods in an industrial way seems time-consuming and unsuitable.

More recently, statistical approaches to assess the data quality have been applied. The so-called Monte-Carlo statistical approach [17] permits one to evaluate the distribution of the results providing the statistical distributions of the initial data are known. Then, in the case of a comparison of the two products A and B, this methodology, in addition to the flux values, evaluates the standard deviation and a confidence index can be calculated, providing useful information for an environmental and pertinent choice. In addition to the frequent incompatibility between software, data distributions are usually assumed without evidence, since Gaussian curves are unknown in most of the cases. The existing methods are not suitable as they are either too time consuming or need unknown parameters.

From the beginning, the Taguchi method which uses factorial plans, allows one to reduce the number of experiments to determine the coefficients of a model. This method has been and is still widely applied to increase the quality and the competitiveness of industrial processes. For example, the objective of an industrial workshop is to produce mechanical parts with a precise length. Then the Taguchi model will give the values the process parameters have to take so that the parts are goods. Some standard tables have been developed by Taguchi and are usually sufficient to cover all the industrial applications. Therefore, as a complement of the analysis done from the inventory, in terms of energy consumption and CO_2 emissions, and the impact assessment, a sensitivity analysis has been carried out with the Taguchi approach in order to determine the driven parameters of the study and to evaluate the robustness of the results.

In this study and as presented in **Table 1**, a 4 level parameter (data source of the polypropylene), 3 parameters with 3 levels (mass of the bumper, transport distance and quantity of electricity), 2 parameters with 2 levels (transport and electricity models) have been studied. If the Taguchi plan is not used, 432 ($1^4 x 3^3 x 2^2$) experiments would have been necessary to determine the driven parameters of the study. With the Taguchi plan, only 32 experiments [18] are necessary and provide the LCA practitioner with the same results. For the PP production data source, the level 1 corresponds to the APME data provided by the Boustead database, the level 2 of the APME data is provided by the IKP database, the level 3 of the data is provided by Buwal and the level 4 of the data is provided by DSM. The models of electricity or transport are extracted from Boustead (level 1) and Ecobilan (level 2) databases. The mass of the bumper and the quantity of electricity consumed during the life cycle are successively the reference value (level 1), the reference -10% (level 2) and the reference +10% (level 3). The transport distances take the value of the reference (level 1), the reference value multiplied by two (level 2) and a value of zero (level 3).

Due to the results of a consistency between the inventory and the impact assessment step pointed out above, the results of the Taguchi plan are only examined at the inventory phase in terms of energy and CO_2 emissions.

4.1 Energy consumption

Fig. 8 illustrates the influence of the parameters on the energy consumption for each end-of-life scenario. This is the maximum variation in the percentage of the energy consumption depending on the values taken by the parameters and, thus, the influence of the parameter is quantified.

It appears that the influence of PP production data source (28%) is important for the scenario incineration with energy recovery. The influence of the PP production data source is roughly 10% for the other scenarios (landfill, recycling 30%, recycling 60%, recycling 90% and incineration without energy recovery). Consequently, it is assumed that the average European data provided by APME are sufficient and it is not necessary to use specific data coming from a particular site.

The influence of the electricity model is less than 4% for each end-of-life scenario. Then, both the Boustead or the Ecobilan model can be used indifferently.

The influence of the transport model is less than 10% for the scenarios of landfill and incineration without energy recovery and more than 10% for the recycling scenarios and

Table 1: Parameters for the Taguchi plan

	Level 1	Level 2	Level 3	Level 4
PP production data source	APME (Boustead database)	APME (IKP database)	Buwal	DSM
Electricity model	Boustead	Ecobilan	-	-
Transport model	Boustead	Ecobilan	-	-
Bumper weight	Reference	Reference - 10%	Reference + 10%	-
Transport distance	Reference	Reference + 100%	0	-
Quantity of electricity	Reference	Reference - 10%	Reference + 10%	-

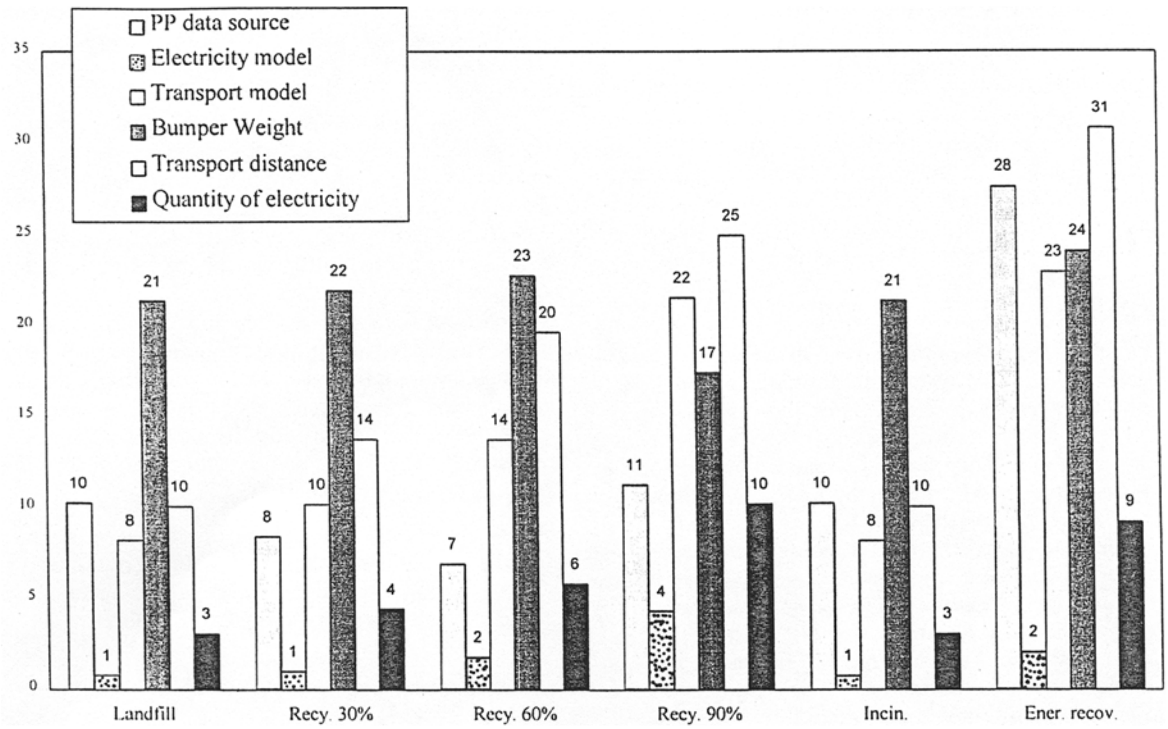

Fig. 8: Influence of the parameters on the energy consumption

the incineration with energy recovery. For the recycling scenarios, the distance remains the same, but the quantity transported changes with the recycling rate. For each model, the empty return of the lorry is taken into account, but the reference is not expressed in the same unit, kg·km for the Ecobilan model and vehicle·km for the Boustead one. Then it is really difficult to compare those two models and, in addition, they are closely related to the petrol delivery model used in each database. The influence of the transport model increases with the recycling rate. The influence increases with the value of 12 between recycling 30% and recycling 90%.

The recycling and incineration with energy recovery scenarios are largely dependant on the modification of the transport distance. For a 30% recycling (resp. 90%), the influence is 45% (resp. 81%). Then the recycling depends on the transport and the geographical situation of the recycling companies. The scenario incineration with energy recovery (resp. landfill) with the value of 46% (resp. 48) is hardly dependant.

The influence of the quantity of electricity for each scenario is less than 10%. Then this parameter does not drive the results and a very precise value for it is not necessary. The variation of the mass bumper induces a constant influence of roughly 20% on the energy consumption for any scenario, except the 90% recycling scenario (37%).

It appears that the influence of the parameters is greater for the scenario incineration with energy recovery. This is due to the fact that this scenario has the lowest total energy consumption and the influences of the parameters are calculated in comparison with the value taken by each scenario (all parameters with the level of 1 within the Taguchi plan).

The driven parameters of the study are the mass of the bumper and the transport distance. Then the results are not conditioned by the methodology or the data chosen from the databases (PP data source, electricity and transport models).

CO_2 emissions. Fig. 9 illustrates the influence of the parameters on the CO_2 emissions for each end-of-life scenario. It is the maximum variation in percentage of the CO_2 emissions depending on the values taken by the parameters. In this way, the influence of the parameter is quantified.

Contrary to the energy consumption, the PP data source has a great influence on the CO_2 emissions. It reaches the value of 95% for the landfill option, 134% for the scenario energy recovery and is never less than 38%. This is due to the use of a particular data source: the Buwal, which provides with old (1984) and uncompleted data (for the PP production no CO_2 emission have been taken into account). Then the APME data should be preferred for the PP production.

The influence of the electricity model depends on the scenario and is between 1% for the incineration without energy recovery, recycling 90% and 12% for the 90% recycling. The influence of the electricity model increases with the recycling rate, it reaches 1% for the 30% recycling and 12% for 90% recycling. For the incineration with energy recovery (resp. without energy recovery), the influence reaches the value of 1 (resp. 5%). The landfill scenario shows an influence of 7%.

The influence of the transport model is between 6% for the incineration without energy recovery and 37% for the recycling 90%. A large quantity of CO_2 is emitted during the

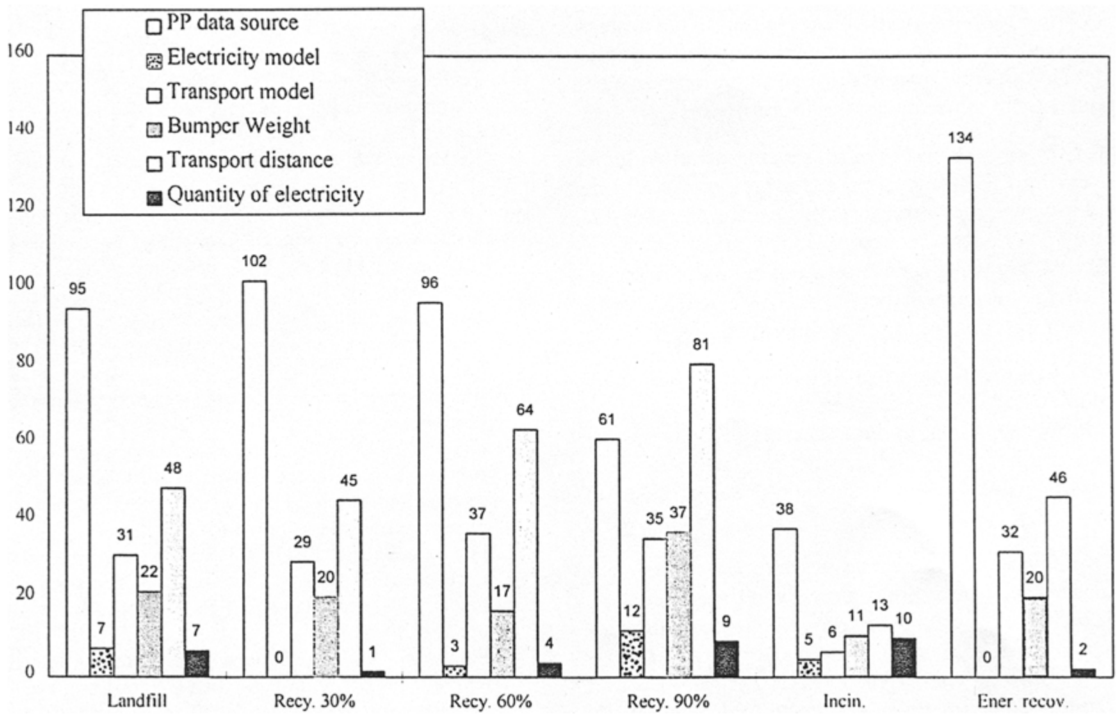

Fig. 9: Influence of the parameters on CO_2 emissions

incineration. In the case of no energy recovery, the total quantity of CO_2 for this scenario (208) is very high compared to the landfill reference (100) (see, Fig. 4). Then, the influence of the transport model appears to be moderate (31%) compared to the total CO_2 emitted for the total life cycle of the incineration without an energy recovery scenario.

The influence of the mass of the bumper reaches the constant value of roughly 20% for the scenarios of landfill, recycling 30% and incineration with energy recovery.

For the transport distances, the influence is greater for the recycling scenarios: it reaches the value of 45% (resp. 81%) for 30% recycling (resp. 90% recycling). The results are less dependant for the scenario incineration without energy recovery. The influence remains important as it reaches the value of 46% (resp. 48%) for the incineration with energy recovery (resp. landfill).

The influence of the quantity of electricity is always less than 10%.

It appears that three parameters (mass of the bumper, distance and transport model) drive the results of the study in terms of CO_2 emissions. But the influence of the PP data source is particularly high only due to the Buwal data that is a particular, old and uncompleted source and should therefore be avoided. The electricity model and the quantity of electricity needed for the complete life cycle do not determine the results of the study.

Interests of the Taguchi plans

In the present study, the Taguchi plan (32 experiments) permitted the ranking of the driven parameters and has shown that the results are mainly conditioned by the study parameters (mass of the bumper and distances of transport). Moreover, there is no influence of the 'methodological' parameters (electricity model, PP production data source), although the inventory results seem sensitive to transport model. It can also be pointed out that no specific software has been necessary and the calculation time has been limited to a couple of hours. Furthermore, no data distributions have been postulated, only reasonable assumptions on the intervals of variation of each variable have been used. Finally, this sensitivity analysis has shown that the geographical and industrial context (road infrastructure, density of recycling centres, number of incinerators) within which the comparison between landfill, recycling and incineration is done, is the clue of the problem. Therefore, it can be stated that no overall advantage of recycling over incineration, or *vice versa*, can be put forward regarding the project of European Directive on Recycling. In the future, the choice between the two alternatives will be rather driven by a deep examination of the real situation (distance of transport, weight of the product, type of materials).

5 Conclusion

The aim of the study was to examine the environmental impacts of various end-of-life scenarios of a PP bumper skin. The existing landfill, taken as the reference, is the starting point and the following end-of-life scenarios have been studied: recycling (with different rates of 30, 60 and 90%), incineration with or without energy recovery. The functional unit encompasses the whole life cycle (material production, injection moulding, transportation of various type and end-

of-life). A closed-loop has been chosen to define the system boundaries in the case of recycling and incineration. Complementary data about air emissions during PP incineration have been obtained from experiments in laboratory.

An inventory (energy) has shown that incineration with energy recovery and 90% recycling are the most favourable scenarios. However, they cannot really be differentiated due to a small gap in energy consumption. Concerning CO_2 emissions, 90% recycling scenario seems to be the best scenario and energy recovery is between 30% and 60% recycling. CO_2 being strongly limited by energy recovery.

The impact assessment using three different methods (EPS, critical volumes and CML) has given the same trends as the inventory. However, a lack of data regarding effects on water of incineration does not allow the evaluation of these scenarios with critical water volume and eutrophication parameters.

The Life Cycle Assessment methodology appears to be very robust and the conclusions point globally in the same direction: either the 90% recycling scenario and incineration with energy recovery are equivalent and clearly the most environmental friendly or energy recovery is between 30 and 60% recycling. However, those results should be carefully used because:

- The incineration model is imperfect and uncompleted as it only considers air emissions.
- Crediting of material benefit due to recycling step is very favourable as it does not represent the loss of raw material quality.

Finally, a sensitivity analysis using Taguchi plans complementing this Life Cycle Assessment has shown that the results are primarily due to the study parameters (mass of the bumper and distances of transport). The influence of the 'methodological' parameters (electricity model, PP production data source) is limited by the transport model. Therefore, no overall distinction between recycling and incineration can be pointed out and the choice must be closely linked to the real context within which the comparison is done.

In an automotive context, LCA are therefore powerful enough to discriminate on a environmental point of view various processes or technologies and they are now currently used at PSA Peugeot Citroën as a decision tool for strategic issues as the end-of-life scenarios or the emissions during the vehicle use. However, LCA appears today to be too immature to help designers owing to the numerous input data and the time required to complete a study.

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